

An Index Of Habitability

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ABSTRACT

Perhaps the greatest challenge facing the Human Factors profession is the ability to communicate effectively with their customers. One example is the NASA Standard 3000, which is an extensive compilation of human factors information, but an inefficient tool in the design and evaluation processes. These shortcomings are indicated by the need for interpretation of much of the material by human factors specialists and the amount of time spent dealing with "waivers." An alternative approach is being developed which provides specific quantitative targets (engineering specifications) for design and evaluation, coupled with a process of continuous improvement. The targets are developed for measurable aspects of the environment or human-system interface, by a consensus of human factors, domain experts and user representatives. This participative approach will ensure "buy-in" by all parties ahead of time and thus reduce the need for waivers. Although variable interactions are key to human factors evaluation, individual factors are often manipulated independently during design. Similarly, this measurement process focuses on individual factors, but provides a clear visual presentation of how these factors may interact.

INTRODUCTION

The safety, health and performance of people living and working in space are affected by the physical, organizational and temporal contexts, the task content and the required activities. These factors interact in complex ways to influence the behavior, performance, safety, health and perceived comfort of crewmembers. These factors will in turn affect likelihood of success or failure of the mission. A challenge for human factors professionals is to accumulate and compare the individual and interacting effects in a manner conducive to evaluation, design and reactive intervention. An associated challenge is to predict when and how a mission or mission element will be compromised.

An objective of a comprehensive measurement tool such as the Index of Habitability is to delegate as much of the design process to the engineers and mission operations planners by providing appropriate, clear and verifiable design requirements. (Figure 1.) The human factors profession has for many years sought to develop, design and evaluate requirements in great detail, but has often failed to address the key element of usability. For example MIL STD 1472, NASA STD 3000 - Manned Systems Integration Standard and handbooks such as Woodson, Tillman and Tillman (1992) "Human Factors Design Handbook" [8] all contain extensive design information. But, one shortcoming of such sources is that they often require time-consuming interpretation by a human factors expert. A second issue is that the separate requirements statements do not formally weight the relative importance of different aspects of the human environment in the context of different activities. A recent effort by the American Bureau of Shipping [1] has produced a comprehensive set of measures of the habitability of ships. These measures provide two ranges - one for crews and a more conservative / comfortable one for passengers.

Using an analogy to the general "triage" concept from the medical community, approximately 70% of habitability questions may be resolved by reference to a more general habitability index, a further 20% will require some interpretation by specialists and the final 10% of questions will require a specific in depth assessment of complex interactions and unusual conditions. This approach is intended to reduce uncertainty from the design process and to free up the scarce human factors resource for the more complex residual design questions.

Gawron's [3] "Human Performance Measures Handbook", and also the "Handbook of Human Factors Testing and Evaluation" edited by Charlton and O'Brien [2] both present extensive reviews of human performance measurement methods in the operational context. A chapter, in the latter book, on "Measurement in Manufacturing Ergonomics" [5] addresses many of the

challenges of the development of a comprehensive, but "user-friendly" design requirements process. One particular emphasis of this discussion is the separation of measurement from policy. Measurement of human performance and the environment is objective and unbiased by outcome. In contrast, design requirements determination is a policy issue. This is because the level of performance that is required, is a product of the performance measurement and the desired level of accommodation (protection) that is deemed appropriate. The desired level of accommodation is determined by weighing the risks, benefits, and costs, etc, or imposing a certain requirement and achieving a certain probabilistic outcome. Thus, design requirements are determined by policy. A familiar example is the measurement of automobile speed, which is a technical issue, and the setting of speed limits, which is a policy issue, based on technical evidence.

The index of habitability is a device that employs a common currency for the understanding of the relative effects and risks of individual and combined contextual and activity stressors. It also permits the consistent comparison of different designs, interventions and habitats. This prototype "HabIndex" is intended to be applied to the assessment of the International Space Station, the Space Shuttle and various earth habitation analogs. Experience to date indicates that it is intrinsically appealing to human factors specialists, engineers, managers and crewmembers.

COMMON CURRENCY

Human Factors professionals are often familiar with scaling methods used on surveys to compare qualitatively different concepts. [3, 2] For example, Lickert Scales are used widely in surveys such as the evaluation of college courses. Verbal or quantitative anchors are used to achieve consistency and avoid bias among subjects in their ratings. The same concept of "common currency" may be applied to such habitability factors as temperature, noise, space, food, hygiene facilities, exercise equipment and so on. The first challenge is to establish a set of variables that are measurable, relevant and amenable to change. The second challenge is to establish ranges for each individual variable for mapping onto the common outcome prediction scale. The final challenge is to develop a means of accumulation and presentation of the data that is useful in the evaluation, decision, design and intervention processes.

An often used "currency" for such assessments is the use of green, yellow and red categories. A drawback of this scale is its level of resolution, which leads to difficulties in amalgamation and interminable discussions of "how yellow is yellow?" The level of resolution chosen for the Index of Habitability is seven usable categories as follows:

Acceptable		Marginal			Unacceptable	
1	2	3	4	5	6	7

Figure 1 The Habitability Index Scale

A classification of "0" is reserved for "not relevant". Classifications 8, 9 and 10 address possible but "Unthinkable" conditions.

An alternative characterization of the use of the overall index in a mission monitoring process could involve the following response levels:

7	Intolerable	Emergency evacuation and return
6	Unacceptable	Emergency ("stand and fight") response
5	Undesirable	Preplanned contingency response
4	Marginal	Mission control intervention
3	Tolerable	Crew autonomous response - monitor frequently
2	Acceptable	Monitor regularly
1	Ideal	Monitor regularly but infrequently

This list indicates how verbal anchors (i.e., 7 = "Intolerable" which should reflect something on the comparable magnitude of "emergency evacuation") may be used to define both the level of risk associated with a particular situation and the form of response.

THE IMPORTANCE OF EVIDENCE AND CONSENSUS.

It must be acknowledged that there are many participants in the evaluation, decision, design and intervention processes, who may have differing views regarding the importance of different variables. Research oriented contributors will emphasize the importance of logic and empirical data in the establishment of the relationship between a specific variable and some outcome. Engineering practitioners will emphasize domain experience and intervention feasibility. Management will address the relative risks and benefits of individual contributions to the total picture. The eventual users of the process may expect

more stringent limits on design parameters, depending on their experience with similar systems and predisposition to tradeoffs such as between speed and accuracy. If the customers for the process (the engineers, managers and eventual users) don't contribute to the chosen limits ahead of time, they are more likely to submit waivers or change requests later. It is well known that late changes cost more than early interventions in most design processes. Also the acceptance of an individual waiver request without due assessment of the effect on total system performance may lead to inappropriate intervention.

The cost of design or change and the tradeoff between benefits and risks of undesirable outcomes will concern the managers. Because of the inherent underlying human, situational and temporal variability, it is essential that managers (or other policy makers such as legislators) provide guidance regarding the degree of protection or acceptable performance levels.

Finally, the end users certainly must have a say in the establishment of limits, if they are to perform well, keep healthy and avoid time consuming and costly changes late in the design process.. The human factors practitioner often has to mediate between these different players in the establishment of evaluation and design requirements. The establishment of design requirements must be a consensus process, with the advantages and disadvantages of design choices worked out before hardware, software, "organizationware" or "liveware" decisions are made."

Given this consensus approach to development, the processes of verification and validation of the index become much easier.

THE IMPORTANCE OF THE ACTIVITY AND TEMPORAL CONTEXTS

Human and environmental requirements are usually affected by the particular activity being undertaken. For example, the temperature conducive to reading will be higher than that for hard physical work. The spatial expectations for "habitability" of a tent on a camping trip, in a home, in a submarine, in an Antarctic outpost, in a hospital ward or in a space vehicle will also be very different. Also, an obstruction that is only encountered occasionally for a non-critical activity will be more tolerable than one that gets in the way during an emergency or is encountered continuously, frequently or for long periods of time. Thus the establishment of scales and limits for the physical context will interact with the demands of the activities that are being carried out. Comprehensive, generic lists of activities, that are expected to be carried out on the International Space Station, are described in Figure 2.

The activity basis is important for the development of the habitability index because the impact of contextual variables is activity dependent. For example, limited visual access may be acceptable for a non-critical

stowage task, but may be crucial for a delicate maintenance task. The importance and failure implications of particular activities also affect the choice of design level. For example, an occasional high force to open a garbage drawer / container may be acceptable, whereas an excessive force for an emergency manual valve could have more serious implications.

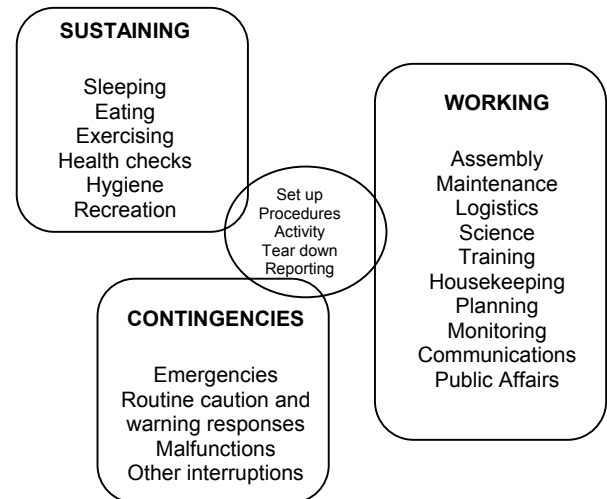


Figure 2 The activities of interest in the current iteration of the Habitability Index

MULTIPLE OUTCOMES

A challenge for the establishment of scales is that the effect of the variable of interest (e.g., water temperature) may not be monotonic. For example water used for bathing should be neither too hot nor too cold; a hatch should be wide enough to pass through, but small enough for crew members in zero gravity to reach the walls for propulsion; loud music may be good for entertainment but not for sleeping; food that is attractive may not always meet nutritional requirements. Working long hours on a maintenance project may be important, but not compatible with longer duration health status and performance capability. Thus some scales may be monotonic, others may be "U" shaped and most will have to deal with non-linearity. The precise relationship will be dependent on the available historical data and domain experience. In this context, because of the underlying noise due to human and situational variability, assumptions of linearity may be sufficient for the purpose of scaling and amalgamation of scales to form an index. However, as designed, the habitability index is compatible with any design-outcome relationship.

TRADEOFFS

Once a design requirement has been stated in objective terms then verification is straightforward. For example there may be a requirement that the diameter of a hatch for emergency egress under microgravity conditions should be not less than 40 inches. In practice however, there may be other factors that pressure the designer to

provide smaller diameters. Such situations commonly lead to debates related to item-by-item "waivers." The approach offered by the Habitability Index is to present the requirement in the form of a range of acceptability, using the common currency metric. Multiple components of the activity based measurement tool are presented side by side and an overall index is calculated. The relative "importance" of separate components is addressed by appropriate choice of cut off points on the measurement range. In this way the designer and management decision maker can make tradeoffs to improve the overall level of habitability by addressing those elements that are either totally unacceptable and / or easy to change.

VERIFICATION OF REQUIREMENTS

A major hurdle in the design of complex systems, such as a space vehicle or closed environment earth analog is the verification of requirements. The components of the index of habitability all relate to objective engineering measures that can be changed if the evidence warrants. If a variable outcome rating is in the "red" zone then this scale value will map into a clear engineering variable. Although complex interactions are the norm in human factors, the use of univariate measures is more conducive to verification and engineering intervention. An extension of the habitability index deals with common interactions by two or more dimensional charts, which allow the engineer to make tradeoffs between different elements of the complex environment.

VALIDATION AND CONTINUOUS IMPROVEMENT

Validation processes present difficult challenges of test construction and subject selection. There is an interesting statement in an ISO display design standard that states: " If a non conforming display element performs satisfactorily in a usability test, then that display element will be deemed to conform." Such statements are a condemnation of the specification development process. The design of this habitability index is such that engineers are not faced with absolute specifications. Rather, they are provided a continuum over the range of interest with the object of achieving the optimal level wherever possible. The scale represents a "loss function" in that the further the design is from the optimal, the greater the "cost" in terms of both the individual variable and overall habitability index. In this way, the engineer or decision-maker may tradeoff values of different variables in order to optimize engineering feasibility, cost and habitability.

The continuous improvement process, commonly used in contemporary manufacturing operations development, should be applied to the overall index, given rules to deal with "red" conditions first. When addressing "yellow" conditions, the choice of which intervention to make will be influenced by likely interactions, cost, and feasibility issues.

COMMON FORMAT

The design of the habitability index is aimed at providing both an overall view of the status of multiple variables associated with a particular activity evaluation and a way of selecting the most promising variables for intervention. The common format - a standard set of tables on one side of a sheet of paper or computer screen / web page - is a familiar medium for all users, thus greatly enhancing the usability. It is envisioned that a family of indices will be developed that deal with such major factors as: environment, workplace, equipment and procedures. Each activity that is evaluated may involve any or all of these major factors that affect human performance. Furthermore, the assessment of a set of design variables may be activity dependent. For example, the optimal thermal environment for sleeping is different from that for exercising.

GENERAL HABITABILITY GROUPS

Because of the complexity of the activities that people are expected to perform and the varied contexts, it is useful to create a sub grouping for assessment purposes:

- Environment
- Workplace
- Equipment
- Tools
- Personal protective equipment
- Procedures, labels and warnings
- Group interactions

These groups contain categorically different measures. For example, environmental variables use well understood physical scales. Workplace and personal protective equipment issues are generally spatial, and equipment interfaces and procedures are primarily cognitive. Group interactions involve both informational and social factors. Variables in these groups also affect human performance in different ways. The procedures, equipment and tools are generally central to the primary task, whereas the environment, workplace and personal protective equipment are contextual factors that modulate primary performance capability. Group interactions may have both primary and contextual effects.

TEMPORAL FACTORS

Human performance capability and tolerance of contextual conditions are usually time dependent. For example a pathway obstruction may be acceptable if the pathway is used once a day, but unacceptable if it is used every few minutes. A moderately loud noise may be acceptable for brief periods but not all day. An inhospitable sleep station may be acceptable for a short duration mission, but not for an extended period of time. These temporal factors - activity frequency and duration,

and mission duration - must be amalgamated with the physical or other variables, in order to establish the index. In some cases the intervention of choice may be a reduction in the exposure, rather than a hardware change. Environmental variables such as heat, noise, air quality and radiation are all compounded by excessive exposures and amelioration may consist of a combination of engineering and operational / exposure interventions.

HABITABILITY INDEX CALCULATION

Because of the complex nature of human response to multiple contextual stresses, it is commonly not possible to precisely specify the interaction effects. Consequently the logic employed in the interpretation of the habitability index is that more stressors are likely to have a greater combined effect than less. Consequently the amalgamation process is limited to the simple counting of stress levels on the common currency scale. Thus a situation that has four "reds" will be ordinal worse than one with 4 "yellows"

An overall picture of multiple variables can be provided by presenting them as an array of elemental conditions associated with general or particular activities. Such a picture will provide the designer or manager with information on which to make tradeoff decisions.

RISK

General human operator failure rates are of the order of 10^{-1} to 10^{-3} per transaction. However, unlike mechanical systems, humans often have the capability of recognizing the failure and making an appropriate corrective action. Humans are also unlike mechanical systems in that they exhibit considerable variability in their propensity for error. Not only do individuals differ, but they may also vary over time, depending on the primary task demands, distractions, prevailing conditions, level of training, fatigue, age, medication and so on. These "performance-shaping factors" may affect the general human operator failure rates by one or two orders. For example, an inebriated driver is not only very likely to initiate a primary failure, but he is also less capable of recognizing and responding appropriately.

Another complication of human failure is that it may be variable in extent. For example in manipulative activities, the human operator will commonly provide an erroneous input that is within the system tolerance. In other situations, human operators may deliberately provide erroneous inputs in order to learn how to control excessive deviations. A familiar example is learning how to control a skid while driving a vehicle on ice. Contextual variables will commonly affect the degree of error and the accuracy and timeliness of response.

The ranges of habitability variables discussed here are chosen to reflect a significant likelihood of modulating operator failure rate probability. For example, cold tired

hands during EVA greatly affect manipulative capability. Similarly noisy environments, although tolerable, may interfere with critical communications. Human operators exhibit vulnerability to cumulative stress in complex ways. For example, poor living and working conditions for long periods of time may at first result in positive adaptation, but later create an increased tendency to failure and inappropriate responses. Human failure is also idiosyncratic, and sometimes appears to be random. Consequently, prediction of human failure propensity can only be carried out by statistical means. Thus habitability stresses will only increase the likelihood of failure and failure per se will be dependent on the prevailing operational conditions and the individual resilience.

Specifically, a habitability index value of 6 or greater (Red) is likely to increase the likelihood of failure by one order. A habitability index value of 5 (Yellow) will almost certainly interact with other variables to cause an increase in failure likelihood. Lower habitability values (3, 4) indicate that the individual variable may interact with other variables. Green assignments (1,2) indicate that that particular level of stress is unlikely to interact adversely with other variables.

Finally, the human perception of risk is unlike the measures of risk based on historical data. Human decisions are based on simple or complex assessments of risk and benefit of alternative actions. Subjective risk perception values commonly differ from objective estimates. The variance in perception also increases as the ratios between risks and benefits approach one. For example most people would agree that a temperature of 100°F presents a high risk of adversely affecting comfort, health, safety and performance. However, many people may be tolerant of 90°F and most of 80°F, depending on the level of physical activity. Thermal "comfort zones" as indicated by population data will range between 70°F and 80°F, but individuals may complain at the extremes of this range. The habitability index acknowledges this human variability and is categorized in "generally noticeable difference" increments rather than the "just noticeable differences" of classical psychophysics.

THE NEED FOR TRAINING

Ideally measurement devices like the Habitability Index are designed with the user in mind. In this case, the users range from human factors specialists, to engineers, to managers and crewmembers. Experience with similar devices in the past [4, 5, 6, 7] has shown that users require training not only in the mechanical use of the device, but also in the underlying principles. Experience has also shown that devices of this nature can be a convenient and effective way of training non-human factors specialists in the technical basis of the subject.

CONCLUSIONS

The habitability index concept is meant to reduce a substantial part of human factors practice to the application of a simple set of rules. In addition, the index is intended to provide a medium for convenient comparison and evaluation of categorically different factors that affect human comfort, convenience, behavior, performance, health and safety. The index is not intended to be used blindly. Rather, it is intended to efficiently screen out major factors affecting human performance, thus freeing up the scarce human factors resources to deal with more complex problems and tradeoffs.

REFERENCES

1. American Bureau of Shipping (2002) "ABS Guide for Crew Habitability on Ships" American Bureau of Shipping, Houston
2. Charlton S.G. and T.G. O'Brien (2002) "Handbook of Human Factors Testing and Evaluation" 2nd Edition, Lawrence Erlbaum, New Jersey
3. Gawron V.J. (2000) "Human Performance Measures Handbook", Lawrence Erlbaum, New Jersey
4. McAtamney L and E.N. Corlett (1993) "RULA: a survey method for the investigation of work related upper limb disorders" Applied Ergonomics 24(2) 91-99.
5. Peacock J.B. (2002) "Measurement in Manufacturing Ergonomics" in Charlton S.G. and T.G. O'Brien (2002) "Handbook of Human Factors Testing and Evaluation" 2nd Edition, Lawrence Erlbaum, New Jersey
6. Chen J, J. B. Peacock and R. E. Schlegel, (1989) "An Observational Technique for Physical Work Stress analysis", International Journal of Industrial Ergonomics, 3 167-176
7. Peacock J. B. and G. Orr, (2001) "A Checklist on Industrial Ergonomics Checklists" Applied Ergonomics Conference, Orlando
8. Woodson W.E., B. Tillman and P. Tillman (1992) "Human Factors design Handbook" Second Edition, McGraw Hill, New York

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